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EVOLUTION OF THE BARRIER
ISLANDS OF SOUTHERN LONG ISLAND, NEW YORK

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ABSTRACT

Three lines of evidence based on data from more than 400 boreholes and vibracores have been used to reconstruct the evolution of the barrier islands during the Holocene transgression in southern Long Island, New York: 1) the Holocene transgressive stratigraphic framework behind the present barriers, 2) the stratigraphic pattern of the inner shelf, and 3) the morphology of the now-buried Late Pleistocene coastal features.

The extensive preservation of backbarrier sediments, dated between 7,000 and 8,000 YBP, on the inner shelf of southern Long Island suggests that the barriers have not retreated by continuous shoreface erosion alone, but have also undergone discontinuous retreat by in-place "drowning" of barriers and overstepping of the surf zone landward. Such surf-zone overstepping would have prevented the backbarrier sediments from being reworked.

It is inferred that about 9,000 years ago, when the sea stood at about -24m MSL, a chain of barriers developed on the present shelf about 7km offshore of the present barriers. The -24 meter barrier built upward with continued sea-level rise until the sea reached about -15m MSL, just prior to 7,000 YBP. The barriers were then overstepped by the rapidly rising sea, and the surf zone skipped landward to a position about 2km offshore of the present shoreline. The surf zone skipped to the landward margin of the old lagoon, which had

become fixed at the steep seaward face of an emerged remnant of a possible mid-Wisconsinan coastal barrier.

A proposed stillstand in sea-level rise at about 7,000 YBP, and marked slowing in the submergence rate thereafter, coupled with increased sand supply from the Pleistocene barrier and glacial-outwash deposits, allowed the new barriers to grow upward with the rising sea. During the past 5,000 to 6,000 years, the shoreface has been retreating continuously. The total distance of shoreface retreat has been about 2 kilometers.

Evidence from southern Long Island and elsewhere in regions of coastal subsidence indicates that rapid sea-level rise and low sand supply seem to favor the overstepping of barriers by the rising sea, whereas slow rates of submergence and a greater supply of sand favor continuous shoreface retreat. Stationary upbuilding, or progradation of barriers may occur when supply of sand is great, and/or submergence is slowed or reversed. Morphologic highs on the pretransgression surface (such as emerged barriers) tend to fix the migrating barrier shoreline during either shoreface retreat or barrier "jumping".

INTRODUCTION

Questions regarding the origin of barrier islands have received a great deal of attention in the geologic literature. Three general hypotheses have been advanced to account for the initial formation of barriers: 1) upgrowth of submarine bars; 2) segmenting by tidal inlets of long coastwise-prograded spits; and 3) submergence of coastal beach ridges by a rising sea (Schwartz, 1971).

DeBeaumont (1845) first suggested that barriers were formed by the upbuilding of offshore bars through wave action. Later Gilbert (1885) suggested that barriers had formed by the growth of elongated spits which subsequently were breached by tidal inlets. Johnson's (1919) acceptance of deBeaumont's hypothesis of submarine-bar upgrowth led to the general adoption of the offshore-bar model (Fisher, 1973).

Sanders (1963) reopened debate on the subject of barrier origin by taking issue with the generally accepted concept of continuous landward retrogression of barriers with submergence as had been proposed by Shaler (1894), Davis (1896) and Johnson (1919). Sanders argued for a revival of the concepts proposed by Gilbert (1885, 1890) who suggested that barriers could be "drowned" in place by a rising sea whereby the shoreline would "jump" landward to the inner margin of the former lagoons. Hoyt (1967) presented an hypothesis of barrier-island formation as a result of the submergence of coastal beach ridges by a rising sea. A similar mechanism had been proposed much earlier by McGee (1890).

Evidence accumulated to date indicates that modern barriers may have been formed by each of these mechanisms, either alone or in combination with one another (Pierce and Colquhoun, 1970; Schwartz, 1971; Field and Duane, 1976). However, the evidence suggests that the mechanism of barrier formation by offshore-bar emergence is not regionally significant (Fisher, 1973; Swift, 1975; Field and Duane, 1976).

Pierce and Colquhoun (1970) defined two kinds of barrier islands: 1) primary barriers which form by engulfment of coastal ridges; and 2) secondary barriers which form seaward of the primary barriers through the longshore growth and later breaching of spits, or by the upbuilding of offshore bars. Schwartz (1971) later suggested that secondary barriers (breached spits or upbuilt bars) would develop during periods of stable or slowly falling sea level, whereas primary barriers (engulfed ridges) would form during periods of rising sea level.

Hoyt (1967) maintained that the absence of open marine-, beach- or shallow-water sediments and fauna landward of many modern barriers on the eastern North American seaboard was conclusive evidence that these barriers did not form as emerged offshore bars or spits, but had originated as drowned beach ridges. He suggested, therefore, that the key to discovering the mechanism of barrier origin was in a study of the sediments beneath the modern barrier-island sands and associated backbarrier-lagoonal sediments.

Although Hoyt acknowledged the possible displacement of the modern barriers from former positions on the continental shelf during the Flandrian submergence, he doubted whether such barriers could have been maintained during the rapid early Holocene rise in sea level.

However, at the time he addressed this question (1967), few data were available concerning submerged barrier- and backbarrier deposits on the continental shelf. It is now established that early Holocene barriers did exist on what is now the continental shelf and that backbarrier- and perhaps barrier sediments are widely preserved on the inner shelf and shoreface off the eastern United States (Dillon, 1970; Field, 1974; Sanders and Kumar, 1975; Swift, 1975; Field and Duane, 1976). Therefore, as recent workers have pointed out, the present-day barriers must be derived from landward-retreating barriers which originated on what is now the submerged continental shelf (Sanders and Kumar, 1975; Swift, 1975; Field and Duane, 1976). Although this does not solve the problem of the original formation of the barriers, somewhere on the present-day shelf, it does indicate that evidence for barrier origin must be searched for not only beneath and behind the modern barriers, but also on the continental shelf and shoreface.

The question of barrier-island origin is directly linked to the problems of the migration of a barrier coast with continued submergence and the modification of a barrier coast, once initiated, by wave activity and longshore drift (Swift, 1975; Sanders and Kumar, 1975; Field and Duane, 1976). In this case, the major questions regarding barriers are: 1) How and when did the barriers become established at a particular location? And, 2) How have barriers behaved during the continued submergence of the eastern North American coast (Field and Duane, 1976)? The answer to these questions lies in a study of the transgressive sediments beneath and behind modern barriers, the depositional record left behind on the shelf by the retreating barriers, and in the nature of the surface being transgressed by the sea. In the present study, these three lines of evidence have allowed a reconstruction of the history of the barrier islands of southern Long Island during the past 9,000 years.

STRATIGRAPHY OF HOLOCENE SEDIMENTS, SOUTHERN LONG ISLAND

The stratigraphy of the Holocene transgressive deposits of southern Long Island and the underlying Upper Pleistocene sequence has been studied using data from more than 400 boreholes, cores, and marsh probings in the barrier- and backbarrier areas. In addition, data from more than 60 vibracores and numerous continuous seismic-reflection (Sparker) profiles were used to study the stratigraphic relationships of the inner continental shelf off Long Island. Locations of the principal boreholes and cores used in this study are shown in Figure 1. Details of the Holocene history of submergence and the Upper Pleistocene stratigraphy have been discussed by the authors elsewhere (Rampino, 1978, 1979; Rampino and Sanders, in prep.). The data from these boreholes and cores have been used to construct two schematic interpretive profiles and sections of the Upper Pleistocene and Holocene stratigraphic units of southern Long Island (Figures 2 and 3).

Upper Pleistocene Stratigraphy

The Holocene transgressive sequence unconformably overlies deposits of late Pleistocene age. The Holocene/Pleistocene contact was recognized on the basis of lithology, degree of compaction and lithification, radiocarbon dating, stratigraphic relationships, and the identification, in many borings and cores, of the weathered pre-Holocene surface. The depth of occurrence of the Holocene/Pleistocene contact in the study area ranges from less than -1 meter MSL in the marshes fringing northern Great South Bay, to -26 meters MSL on the inner continental shelf. The underlying Upper Pleistocene units consist of glacial outwash and intercalated backbarrier- and barrier-island deposits (Fig. 3).

Two units of brown glacial outwash sands and gravels have been recognized, a lower outwash unit (the Merrick Formation) and the upper outwash unit of southern Long Island (the Bellmore Formation) (Rampino, 1978 ms.; in preparation). Interbedded between the two outwash units are Upper Pleistocene (mid-Wisconsinan?) barrier and backbarrier deposits, the Wantagh Formation. The Wantagh deposits consist primarily of gray, compact silty clays and silty sands of backbarrier origin (the silty-clay facies of the Wantagh Formation), but also contain a lens of coarse-to fine-grained sands of inferred barrier-island origin (the sand facies of the Wantagh Formation) that occurs beneath the modern barrier.

These Pleistocene barrier sands may be differentiated from the modern barrier sands by their higher degree of compaction. One radiocarbon date of peat and shell material from the Wantagh Formation has yielded an age of 28,150 YBP (Dietrich, 1976). These Upper Pleistocene units unconformably overlie deposits of Late Cretaceous age, the nonmarine Matawan Group and the marine Monmouth Group of glauconitic sands and silty clay (Fig. 3).

Stratigraphic relationships within the Pleistocene deposits suggest that during late Pleistocene time (mid-Wisconsinan?), a barrier island with a backbarrier lagoon existed in the area of present-day southern Long Island. Judging from similar late Pleistocene barrier ridges preserved elsewhere on the Atlantic Coastal Plain (Winker and Howard, 1977), this barrier ridge may have originally reached heights of 5 to 10 meters above the adjacent lagoonal deposits. In the borings studied by us, it is evident that the original barrier ridge has been eroded by processes related to migration of inlets in the overlying modern barriers (Fig. 3). It is therefore probable that the morphology of the southern Long Island area prior to the Holocene transgression was marked by a linear ridge of Upper Pleistocene barrier sands projecting perhaps 10 meters above the surrounding lowlands (Fig. 4).

Holocene Transgressive Stratigraphy of Southern Long Island

The Holocene transgressive deposits beneath and behind the barrier islands in south-central Long Island take the form of a seaward-thickening wedge, from thin marsh deposits fringing the northern or mainland shore of the lagoons, to more than 33 feet (10 meters) of lagoonal silty clays and back-barrier sands directly behind the modern barriers. These Holocene coastal sediments show a vertical- and horizontal sequence produced by the movement of successive environments of deposition landward and upward with the Flandrian transgression. Seaward of the barriers, the transgressive sediments thin again (Figs. 2 and 3).

The surficial transgressive sequence on Long Island, described from land to sea, is as follows: 1) the submerged Pleistocene highland; 2) the fringe of brackish- to fresh-water marsh; 3) lagoonal-margin salt marsh composed primarily of Spartina grasses; 4) open-lagoonal silty clays; 5) back-barrier tidal-delta and washover sand lobes; 6) backbarrier-fringe salt marshes; 7) barrier-island sands of dunal, beach-ridge, beach-berm, and inlet-fill origin; 8) shoreface sands; and 9) shallow inner-shelf sands. The vertical transgressive sequence is produced as these environments of deposition overstep one another with sea-level rise (Rampino and Sanders, in prep.). This produces an onlap sequence of deposits (Curray, 1964).

In this way, the landward sequence of horizontal environments is repeated in the vertical stratigraphic section (=Walther's Law). Changes in the rates of submergence have been determined through radiocarbon dating of basal backbarrier peats (Fig. 5) (Rampino, 1979; Rampino and Sanders, in prep.).

A typical vertical sequence, as encountered in the many borings in the barrier- and backbarrier areas of south-central Long Island is shown in Figure 6. It shows that the vertical sequence encountered by the drill includes all the sedimentary facies encountered in horizontal landward order on the present coast. This is generally true, except in places where later inlet scour has reworked the sequence (Kumar and Sanders, 1974; Susman and Heron, 1979).

The apparent absence of beach deposits or open-marine sediments in the Holocene sequence behind the present-day barriers argues against the origin of these barriers by emergence of offshore bars or simple longshore growth of spits (Hoyt, 1967, 1968).

The leading edge of the transgressive sequence is formed by the fringing fresh- to salt-water marshes composed of Spartina, Distichlis and Phragmites vegetation. As submergence progresses, these marsh deposits transgress landward over the Pleistocene surface; the former marsh environment is overstepped by lagoonal silty clays. The lagoonal environment is similarly transgressed by backbarrier-lagoonal sands and tidal-delta sands (Kraft, 1971; Rampino and Sanders, in prep.). A fringing backbarrier marsh often develops on protected tidal-delta and washover areas. This marsh surface is subsequently subject to burial by washover of barrier sands during severe storms. This washover process, coupled with erosion of the shoreface, may lead to a landward retreat of the barrier in a tank-tread fashion, exposure of backbarrier sediments on the shoreface, and partial destruction of the Holocene depositional record (Fischer, 1961; Kraft, 1971; Swift and others, 1971; Swift, 1975). However, the transgression might not be continuous, but apparently can occur in "jumps" during periods of rapid sea-level rise (Gilbert, 1885; Sanders and Kumar, 1975). In this case, the transgressive backbarrier deposits would not be destroyed by shoreface erosion, and an almost complete sedimentary record could be preserved on the inner continental shelf. Sanders and Kumar (1975) have suggested that in southern Long Island, during the last 8,000 years, both continuous shoreface retreat and discontinuous "jumps" of the shoreline have taken place.

Holocene Deposits on the Shoreface and Inner Shelf

Study of a suite of vibracores from the Long Island inner shelf and shoreface, collected in depths of water ranging from -16 feet (-5 meters) to -73 feet (-23 meters) MSL, has revealed the presence of typical backbarrier sediments.

Lagoonal silty clays, salt-marsh peat, and gray, backbarrier sands and silty sands have been recovered in more than forty vibracores (Fig. 7). These backbarrier sediments exhibit a typical transgressive sequence of backbarrier sands overlying lagoonal silty clays and marsh sediment which in turn overlie Upper Pleistocene deposits (Rampino and Sanders, in prep.).

A generalized vertical succession of the Upper Pleistocene stratigraphic units of the south-central Long Island inner shelf, constructed using data from the vibracores examined in this study, is shown in Figure 8. In the vibracores studied, a usually thin (0 to 3 meters) layer of modern, reworked shelf sand (the shelf surficial sand sheet of Swift, 1968), taking the form of a series of ridges and swales, overlies the back-barrier lagoonal deposits. The surficial shelf sands are usually separated from the underlying backbarrier sediments by an erosional unconformity. The offshore sediments directly overlie the backbarrier sediments with no intervening barrier deposits.

The backbarrier-lagoonal sequence preserved on the Long Island shelf varies in thickness from 0 to more than 8 meters. These backbarrier sediments have been dated in the present study in two vibracores at between 7,000 to 8,000 YBP (Fig. 5) (Rampino, 1979). Similar-age backbarrier deposits have been recovered in cores from comparable depths on the shoreface and inner shelf off southern Long Island (Kumar, 1973; Sanders and

Kumar, 1975; Dietrich, 1976; Williams, 1976; Rampino, 1979), and from other areas of the middle Atlantic Bight (Swift, 1975; Field and Duane, 1976).

The backbarrier sequence has been somewhat eroded in the present nearshore zone; in many vibracores, the backbarrier sands in the upper part of the sequence are thin. However, some core sections preserve almost the entire transgressive sequence of backbarrier deposits; these sequences could not have undergone large-scale erosion. It is difficult to reconcile the preservation of these deposits with the idea that the shoreface has retreated by continuous erosion and washover. If the breaker zone had passed continuously across these lagoonal deposits, they should have been almost entirely reworked (Swift, 1968; Swift and others, 1971; Swift, 1975).

THE EVOLUTION OF BARRIERS AND PRESERVATION OF THE TRANSGRESSIVE SEQUENCE ON THE INNER SHELF

Two contrasting hypotheses have been advanced regarding the response of barrier islands to a marine transgression, and the possibilities for preservation of the backbarrier sediment on the inner shelf (Fig. 9). The most widely held hypothesis is that of "shoreface retreat" (Swift, 1968; Swift and others, 1971; Johnson, 1919). This view states that as sea level rises, the barriers migrate continuously landward in a tank-tread fashion through the combined effects of shoreface erosion and washover on the landward sides of the barriers. During the migration, the breaker zone traverses the entire area submerged. This continuous shift in the shoreline would lead to complete or almost complete destruction of the backbarrier sediments exposed to wave reworking on the shoreface. The contrasting view, that of in-place "drowning", states that as sea level rises, the barrier may remain in place, while the lagoon on its landward side deepens and widens. Eventually, the breaker zone reaches the level of the top of the barrier superstructure, the sea drowns the barrier, and the breaker zone skips landward to form a new barrier shoreline along the landward edge of the former lagoon (Gilbert, 1885; Sanders, 1963; Sanders and Kumar, 1975; Friedman and Sanders, 1978). When the barriers are drowned in place, the surf zone does <u>not</u> pass continuously across the area in successive leaps. In this way, the entire transgressive sequence could be preserved locally on the inner shelf.

These two contrasting types of barrier-island behavior during a transgression may be related to the balance between the rate of rise of sea level and the rate of sediment supply (Kraft, 1971; Sanders and Kumar, 1975).

In this interpretation, the degree of the retention of the coastal-sediment record on the inner continental shelf depends upon the dynamics of sea-level rise. According to Kraft (1971), slow sea-level rise would favor destruction of the record, as the barrier is eroded back and the transgressive deposits are exposed to wave reworking. By contrast, rapid rise of the sea would tend to favor local retention of the record, as the advancing sea would have less time to rework the backbarrier sediment. However, any form of continuous sea-level rise that exposes such transgressive to deposits in the surf zone would appear likely to destroy most of the transgressive sequence because only a few minutes of wave action are required to rework such deposits. By contrast, rapid sea-level rise may also cause the surf zone to jump landward, across the existing lagoon (Sanders and Kumar, 1975). In this way, much of the transgressive sequence could be preserved on the inner shelf.

Very low rates of relative sea-level rise, or stillstands of the sea, might allow the barrier to build upward and/or prograde (Swift, 1975). The same would be true if a large supply of sand were available from offshore or through long-shore drift. If enough sand were available for barrier nourishment, such upward building could keep pace with sea-level rise. However, continuous rise in sea level would increase the submarine surface area of the barrier, and therefore, more sand would be required to nourish the barrier (from offshore and through longshore drift), while the widening lagoon would trap any fluvial sands. Shideler and others (1972) maintain that when the supply of sand is no longer sufficient to keep pace with the rise in sea level, the barrier would simply begin retrograding by shoreface erosion. However, at that point, the barrier, with its wide and deep lagoon, may be so unstable that in-place "drowning" would occur with the shoreline skipping to the landward margin of the lagoon. This is equivalent to the discontinuous depositional transgression of Curray (1964), in which barriers grow upward, and are later overstepped.

THE EFFECTS OF PRE-HOLOCENE MORPHOLOGY ON THE MIGRATION AND EVOLUTION OF BARRIERS

Emerged barrier-island ridges of late Pleistocene age are common on the Atlantic Coastal Plain (Winker and Howard, 1977). The results of the present study indicate that an emerged Pleistocene barrier ridge of possible mid-Wisconsinan? or late Sangamonian? age existed in south-central Long Island prior to the Flandrian Transgression (Fig. 4) (Rampino and Sanders, 1977; Rampino and Sanders, in prep.).

An interpretation of the events that would take place as a migrating barrier shoreline encountered such an older barrier ridge is shown in Figure 10 . In either case, shoreface retreat, or barrier "jumping", the Pleistocene barrier ridge would tend to localize the new barrier shoreline. In the process of shoreface retreat (Fig. 10A, B), the barrier would intercept the Pleistocene shoreline and would become "welded" against the older ridge (Field and Duane, 1976). This process would tend to fix the new shoreline until either sufficient sea-level rise took place to overtop the barrier, or continuous shoreface retreat caused the shoreline to migrate past the old barrier ridge.

In the process of in-place "drowning" (Fig. 10C, D), the Pleistocene ridge would at first fix the landward margin of the lagoon (for example: the southern New Jersey coast; Halsey and others, 1977). After the migrating barrier has been drowned and the shoreline has "jumped" to the landward, it would naturally jump to the Pleistocene barrier ridge

(Gilbert, 1885). In this way, the modern barrier would be built on top of the older barrier shoreline.

Many barriers on the Atlantic Coast of the United States and elsewhere have been found to be built on top of, or resting against, older Pleistocene barrier ridges, many of which have yielded mid-Wisconsinan radiocarbon age determinations (Hoyt and others, 1968; Pierce and Colquhoun, 1970; Kraft, 1971; Orme, 1973; Oaks and Dubar, 1974; Mixon and Pilkey, 1976; Susman and Heron, 1979; Field and Duane, 1976; Halsey and others, 1977). Therefore, it appears that late Pleistocene barrier ridges have acted as nuclei that helped localize the initiation of many modern barriers (Fig. 11)

Once initiated, these barriers would undergo modification thro longshore spit progradation, coastal straightening and s face recession (Pierce and Colquhoun, 1970; Swift, 1975; Field and Duane, 1976).

The evolution and migration of barrier islands with rising sea level appears to be largely determined by: 1) the rate of relative sea-level rise balanced with the supply of available sediment from erosion of the mainland, offshore sands, or by longshore drift; and 2) the nature of the surface being transgressed. The following section presents an interpretation of the history of the southern Long Island barriers during the past 9,000 years based on the evidence obtained in the present study.

DISCUSSION: RECONSTRUCTED HISTORY OF THE BARRIERS OF SOUTHERN LONG ISLAND

Sanders and Kumar (1975) have presented an interpretation of the history of the barrier islands of southern Long Island for the past 9,000 years. The presence of back-barrier sediments dated at between 7,000 and 8,000 YBP on the inner shelf and shoreface, and indications of drowned barrier sands in seismic records, led Sanders and Kumar to infer that when sea level stood at about -24 meters MSL, about 9,000 years ago, a chain of barriers existed approximately 7 kilometers offshore parallel to the trend of the modern shoreline (Fig. 12a). These barriers were similar in size to the present-day barriers. As the sea continued to rise, this system of barriers remained in place and built upward until the sea rose to -16 meters MSL, about 7,500 YBP. According to Sanders and Kumar (1975), at -16 meters MSL, when sea level had reached the level of the top of the superstructure of the -24 meter barrier, the surf zone "jumped" 5 kilometers landward to form a new shoreline 2 kilometers offshore from the modern shoreline. New barriers formed at the -16 meter shoreline; these barriers were the direct "ancestors" of the modern barriers. According to this interpretation, the barriers which formed at -16 meters about 7,500 YBP have migrated continuously landward (about 2 kilometers) as the sea rose from -16 meters MSL to its present level. In this way, the barriers of southern Long Island during the last 9,000 years were inferred to have shown a history of both inplace "drowning" and shoreface retreat.

If the scenario of Sanders and Kumar is correct, the shoreline jumped to a position about 2 kilometers offshore of the modern shoreline about 7,500 YBP. The extensive preservation of backbarrier sediments directly overlain by offshore marine sediments on the inner continental shelf seaward of that position, encountered in many vibracores, supports the idea of discontinuous jumps in the surf zone. As explained previously, if the surf zone had traversed the entire inner-shelf area, as continuous shoreface retreat demands, these backbarrier sediments are not likely to have survived reworking.

Partial preservation of the backbarrier deposits during continuous shoreface retreat may be possible if lagoonal deposits are originally very thick (as they might be on a coastline of steep gradient) (Swift, 1975). This may explain the partial preservation of the backbarrier sequence in some cases on the inner 2 kilometers of the shoreface of southern Long Island, in a zone where continuous shoreface retreat is inferred to have taken place. It is interesting to note that it is in just this zone that the pre-Holocene surface steepens, where underlain by fans of glacial outwash (Fig. 3).

The evidence uncovered in this study of the Holocene sediments and underlying Pleistocene deposits of southern Long Island and the adjacent inner continental shelf suggests a modification of this inferred history of barrier migration. The study also provides evidence for two important controlling factors in the migration of barriers: 1) morphologic highs in the Pleistocene surface being transgressed by the sea; and 2) marked changes in the rate of relative sea-level rise and sediment supply.

The presence of backbarrier sediments dated at 7130 $\pm$ 380 YBP at a depth of -16.6 meters MSL on the inner shelf (Rampino, 1979) (Fig. 5) is an indication that the barriers at -24 meters were not drowned until sometime <u>after</u> 7,130 YBP.

During a period of relatively rapid sea-level rise just prior to 7,000 YBP (Rampino, 1979), the -24 meter barrier-island chain which existed about 7 kilometers offshore of the present barriers was overstepped, and the shoreline jumped landward to a position about 2 kilometers offshore of the present shoreline (Sanders and Kumar, 1975). The surf zone is inferred to have skipped to the landward margin of the old lagoon, which had become fixed at the steep seaward face of an emerged, older Pleistocene (mid-Wisconsinan?) coastal barrier (Fig. 12a). This Pleistocene barrier localized the new shoreline and provided the nucleus for the growth of a new chain of barriers (Fig.12b). Morphologic highs on the old barrier superstructure would have acted as headlands which localized longshore transport and led to the development of coastwise prograding spits (Pierce & Colquhoun, 1970). Through this method of beach detachment and coastwise spit progradation, the new chain of barriers became established about 7,000 YBP, when sea level stood at about -15 meters MSL.

It is probable that a stillstand, or slight negative oscillation, in relative sea level along the southern Long Island coast at about 7,000 YBP (Caldwell and Sanders, 1973), with attendant increase in available sediment supply from the older barrier substrate, allowed the new barriers to become well established and may have caused the barriers to prograde slightly and build upwards (Swift, 1975).

The generally slow relative sea-level rise in southern Long Island during the last 7,000 years (Rampino, 1979) and the abundant sediment supply from longshore drift, first from the Pleistocene barrier complex and subsequently from the Pleistocene outwash sands of southeastern Long Island, favored the upward growth of the barriers. Landward shoreface retreat with the rising sea level has been occurring for about the last 5,000 to 6,000 years. This modern barrier migration by erosional retreat of the shoreface and related storm washover is presently taking place at an average of 63 cm/year on the southern Long Island coast (Shepard and Wanless, 1971). Total barrier retreat during the last 5,000 to 6,000 years has been in the order to 2 kilometers, based on the subsurface position of the Pleistocene barrier-fixed shoreline of 7,000 YBP (Fig. 13). This indicates that rates of barrier erosional retreat in southern Long Island during the last 6,000 years were on average about 30 cm/year, half the present rate of retreat.

In this way, during the past 9,000 years, the barrier islands of southern Long Island are inferred as having shown a history of both in-place "drowning" and continuous shoreface retreat. The behavior of the barriers with rising sea level and transgression appears to depend strongly on the rate of relative sea-level rise balanced with the supply of sediment from various sources available to nourish the barriers, and on the presence of morphologic highs, most notably older, emergent Pleistocene barrier shorelines, on the surface being transgressed.

Rapid sea-level rise and low sand supply seem to favor the overstepping of the barriers by the sea, whereas slow sea-level rise and a greater supply of sands appear to favor continuous shoreface retreat. However if the submergence is very slow, or if stillstands take place, and/or sediment supply is very great, stationary barrier upbuilding and perhaps progradation may take place. The presence of morphologic highs on the pre-transgression surface tends to localize the migrating barrier shoreline during both continuous shoreface retreat, and shoreline "jumping".

The tendency for barriers to develop adjacent to, or on top of, older barrier ridges could produce vertical sequences in which several generations of barrier complexes overlie each other. This would greatly complicate the interpretation and dating of the barrier- and backbarri sequences: It indicates that detailed subsurface sampli and careful dating are required to reconstruct the history of multiple barriers which have been superimposed upon one another as the barriers migrated with the many transgressions and regressions of the Pleistocene sea.

CONCLUSIONS

The questions of barrier-island origin in southern Long Island, New York, and the behavior of barriers during transgression have been addressed using data on the submergence history and transgressive stratigraphic pattern of southern Long Island, the stratigraphic relationships of the Holocene sediments underlying the inner shelf, and the morphology of the Upper Pleistocene deposits. About 9,000 years ago, when the sea stood at -24m MSL, a chain of barrier islands existed on the present shelf about 7 km offshore of the present barriers (Sanders and Kumar, 1975). The -24 meter barriers built upward with the continued sea-level rise until the sea reached about -15 meters MSL, just prior to 7,000 YBP. The barriers were then overstepped by the rapidly rising sea, and the surf zone skipped landward to a position about 2 kilometers offshore of the present shoreline. In this way, backbarrier deposits were extensively preserved on the inner continental shelf. The surf zone skipped to the landward margin of the old lagoon, which had become fixed at the steep shoreward face of an emerged coastal barrier of possible mid-Wisconsinan age.

The barrier of late Pleistocene age localized the new shoreline and acted as a core of growth for a new chain of barriers. The new barriers developed both by detachment of the old barrier superstructure and as spits prograding coastwise from headlands of the older barrier deposits.

An inferred stillstand or negative fluctuation in sea-level rise at about 7,000 YBP, and a marked slowing in the submergence rate thereafter, coupled with increased sediment supply from the Pleistocene barrier and glacial outwash deposits through longshore drift, allowed the new barriers to grow upward with the rising sea.

For the past 5,000 to 6,000 years, the shoreface has been retreating. During this time, the modern barriers have retreated about 2 kilometers. The rates of barrier-erosional retreat in southern Long Island during the last 6,000 years have averaged ∿30 cm/year, about half the present rate. In this way, during the past 9,000 years, the barrier islands of southern Long Island have undergone both in-place "drowning" and continuous shoreface retreat.

Evidence from southern Long Island and elsewhere indicates that rapid sea-level rise and low sand supply seem to favor the overstepping of barriers by the rising sea, whereas slow rates of submergence and a greater supply of sand favor continuous shoreface retreat. Stationary upbuilding of barriers or progradation may occur at times during which submergence is slowed or reversed, and/or when the supply of sand from longshore drift and other sources is particularly great. Morphologic highs on the pre-transgression surface (such as emerged barriers) tend to fix the migrating barrier shoreline during either shoreface retreat or barrier "jumping". Barrier islands tend to develop adjacent to, or on top of, a core of older barrier ridges.

This would produce vertical sequences of multiple barrier complexes, and indicates that proper understanding of such multiple barriers requires detailed subsurface sampling and careful dating procedures.

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Chuck Dill of Ocean-Seismic Survey, Inc. provided vibracore- and seismic-reflection data, and Richard Pardi of Queens College carried out the radiocarbon age determinations reported here.

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FIGURE CAPTIONS

Fig. 1. Location map of study area in south-central Long Island. Figure shows the locations of principal borings used in this study and the location of schematic interpretive profiles and sections A - A^1 and B - B^1. Radiocarbon dated cores are shown by *.

Fig. 2. Schematic-interpretive section A to A^1 through Cedar Beach barrier island.

Fig. 3. Schematic interpetive section B to B^1 through Jones Beach barrier island.

Fig. 4. Reconstructed profile and section of south-central Long Island prior to the Holocene transgression showing mid-Wisconsinan? barrier and facies of the Wantagh Formation.

Fig. 5. Submergence curve for southern Long Island during the past 8,000 years (solid curve). The curve is based on radiocarbon-dated samples reported in this paper (large solid circles) and on previously published dates from northern Long Island (Caldwell and Sanders, 1973; Williams, 1976; Newman, 1977) (crossed solid circles) southern Long Island (Kumar, 1973; Williams, 1976) (small solid circles), and Iona Island, New York (Newman and others, 1969)

(open circles). The dashed and dotted curve indicates possible submergence rates of ∿50 cm/100 years prior to 7,000 YBP suggested for adjacent areas (Sanders and Kumar, 1975). An assumption of relatively smooth change in sea level has been made in constructing these curves.

Fig. 6. Schematic interpretation of a typical transgressive sequence in the backbarrier area of south-central Long Island.

Fig. 7. Location map of vibracores from the inner shelf and shoreface of southern Long Island used in this study. Vibracores containing inferred backbarrier sediments are shown by *.

Fig. 8. Generalized section of Holocene deposits encountered in vibracores.

Fig. 9. A and B. Johnson's (1919) concept of barrier retreat during a rise of sea level (level 1 to level 2). Landward-retreating barriers override the lagoonal sediments (HT = high tide; LT = low tide; figure not drawn to scale). Modifications to this concept have been suggested by Fischer (1961) and Kraft (1971). These modifications suggest that while the sea level is rising, the width of the lagoon remains constant. Johnson's concept implies the following sequence during

shoreface retreat: barrier-lagoon to barrier-marsh, and hypothetically to barrier-against-mainland. In either case, the former lagoonal sediments would be "exhumed" on the seaward side of the barrier.

C and D. Gilbert's concept of barrier drowning "in place" during a rise of sea level (levels 1 through 3). As the sea level rises from SL_1 to SL_2, the barriers remain in place and a "transgression" takes place on the landward side of the lagoon, whereas a "regression" takes place on the seaward side of the lagoon (Fig. 18C). As the sea level rises further (Fig. 18D), the barriers are "drowned" in place, and a new barrier may be established at SL_3 (Figure not drawn to scale) (after Sanders and Kumar, 1975).

Fig. 10. The effects of emerged older barrier ridges on the migration of barriers.

A and B. Behavior of barriers during continuous shoreface retreat, as the sea rises from sea level 1 to sea level 2. Barriers (I) established at sea level 1 retreat landward. When these retreating barriers encounter the Pleistocene barrier ridges (P), the shoreface becomes fixed at the other barriers. The new barrier shoreline (II) will remain at the Pleistocene barrier until either sufficient sea-level rise occurs to overtop the Pleistocene barrier ridge, or continuous shoreface retreat equivalent to the width of the Pleistocene barrier occurs.

C and D. Behavior of barriers during in-place "drowing" with sea-level rise. As the sea rises from sea level 1 to sea level 2, the barrier (I) is drowned and the surf zone skips landward to the margin of the former lagoon. This landward lagoon margin has been fixed at the seaward slope of an older Pleistocene barrier ridge (P). With continued sea-level rise to sea level 3, the new barrier (II) builds upward and retreats landward.

Fig. 11. A. Portion of the Virginia-North Carolina Coast showing Pleistocene barrier ridges of possible mid-Wisconsinan age (Sand Bridge Fm.). Note position of modern barriers adjacent to the older ridges (after Swift et al., 1971).

B. Schematic profiles and sections of North Carolina coast showing Pleistocene barrier and backbarrier silty clays. Note the position of Pleistocene barriers localizing the modern lagoon margin, and the modern barrier built on top of a possible mid-Wisconsinan barrier in section A (after Swift, et al., 1971).

Fig. 12a. Reconstruction of the southern Long Island coast just prior to 7,000 YBP. Locations and trends of the 7000 YBP barrier islands and the inferred mid-Wisconsinan ? barriers are schematic.

12b. Reconstruction of the southern Long Island coast at about 6,000 YBP. Location and trends of the barriers and shorelines are schematic. Dotted lines show the position of the modern barriers and lagoonal shoreline.

Fig. 13a. Position of barrier islands on the southern Long Island coast at about 6,000 YBP. Relative sea level was at about -13 meters MSL at that time. The Pleistocene barrier ridge ("A" indicates the position of the "toe" of the Pleistocene barrier) fixed the position of the new barrier during a barrier "jump" at about 7,000 YBP. Subsequent slowing of relative sea-level rise allowed the barriers to build upward and seaward.

13b. Schematized profile and section of the modern barrier island of south-central Long Island. The barrier has retreated approximately 2 kilometers, from position A to position B, by continuous shoreface retreat during the last 5,000 to 6,000 years.

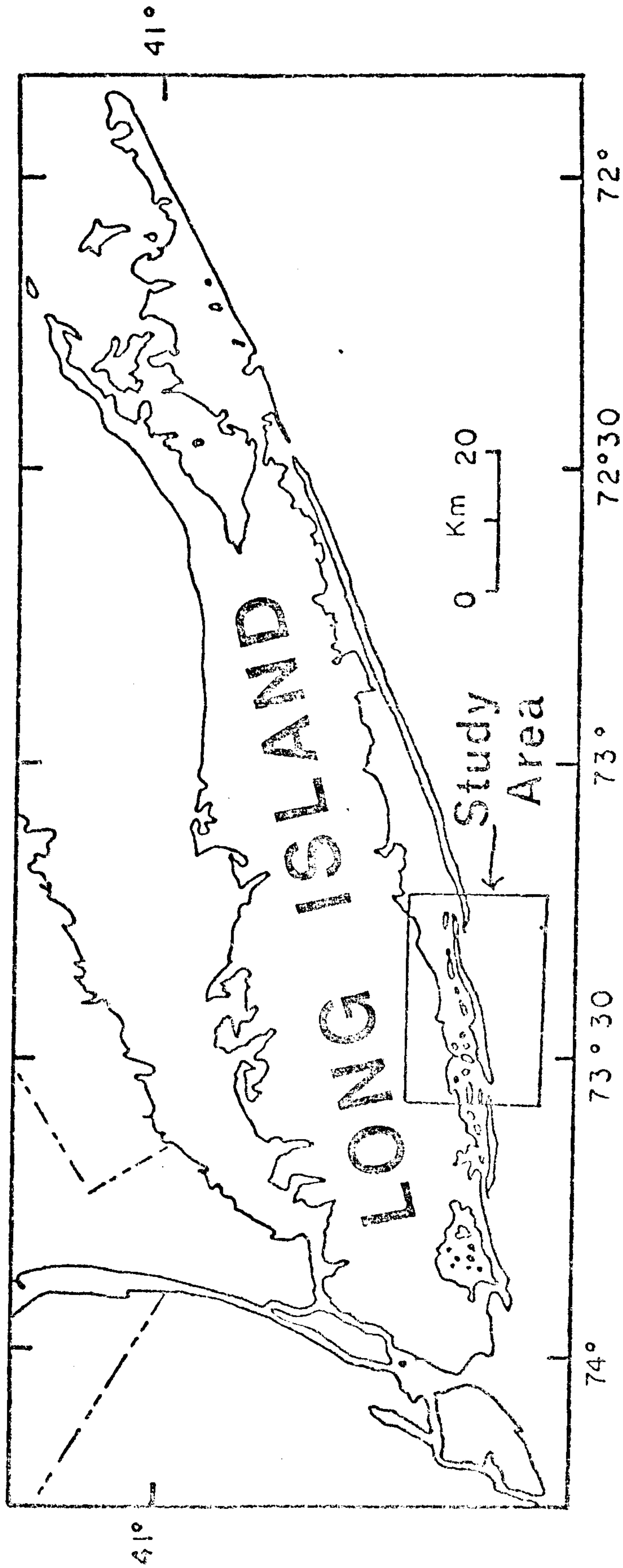


Figure 1A

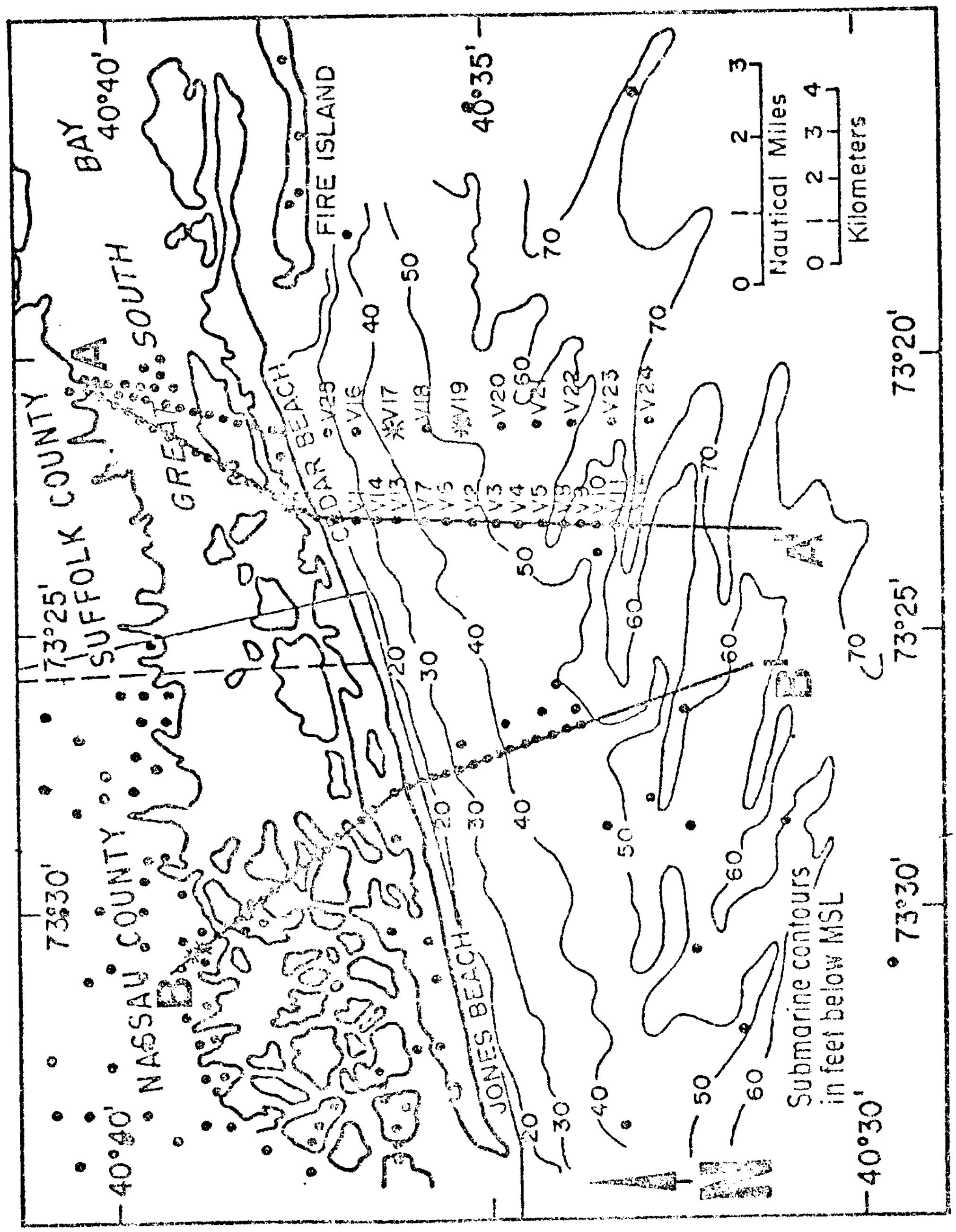

SUFFOLK COUNTY
NASSAU COUNTY
GREAT SOUTH BAY
FIRE ISLAND
CEDAR BEACH
JONES BEACH
73°30'
73°25'
73°20'
40°40'
40°35'
40°30'
Nautical Miles
Kilometers
Submarine contours in feet below MSL

FIGURE 1B

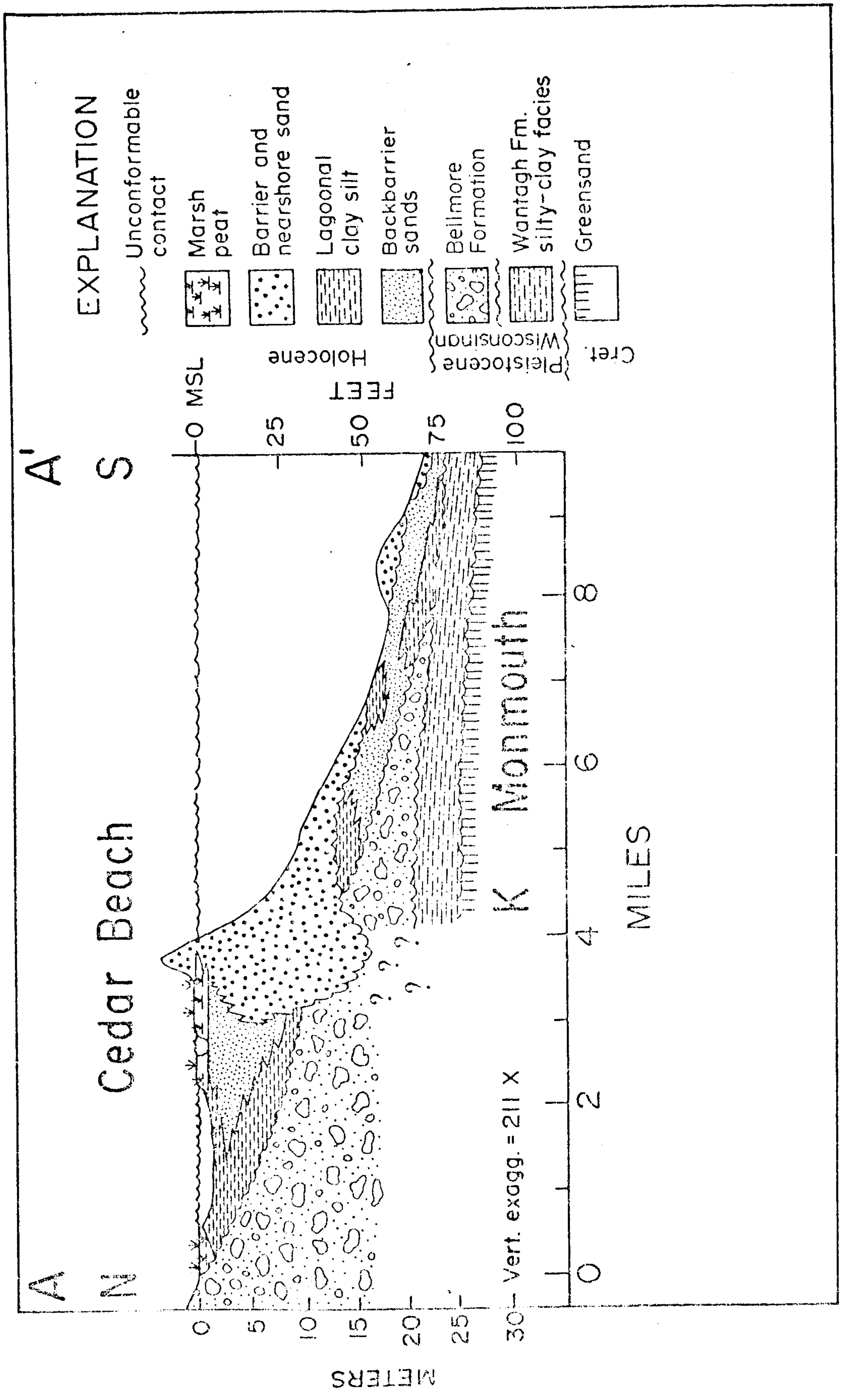
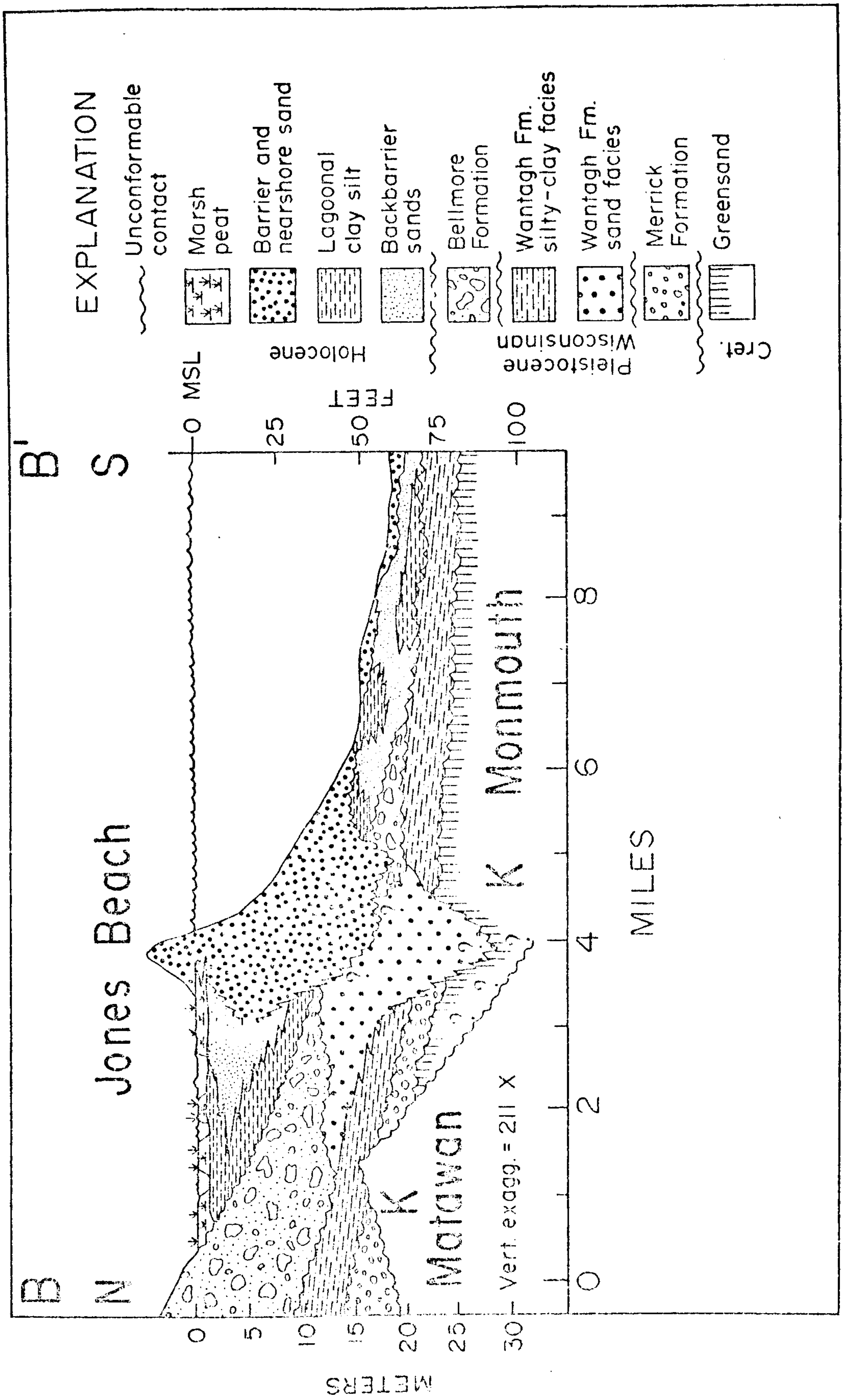

A
N
A'
S
Cedar Beach
K Monmouth
Vert. exagg. = 211 X
MILES
0
2
4
6
8
METERS
0
5
10
15
20
25
30
FEET
0 MSL
25
50
75
100
? ? ? ?
EXPLANATION
Unconformable contact
Marsh peat
Barrier and nearshore sand
Lagoonal clay silt
Backbarrier sands
Bellmore Formation
Wantagh Fm. silty-clay facies
Greensand
Holocene
Pleistocene
Wisconsinan
Cret.

FIGURE 2



B
N
B'
S
Jones Beach
Matawan
K
K
Monmouth
Vert. exagg. = 211 X
MILES
0
2
4
6
8
METERS
0
5
10
15
20
25
30
FEET
0 MSL
25
50
75
100
EXPLANATION
Unconformable contact
Marsh peat
Barrier and nearshore sand
Lagoonal clay silt
Backbarrier sands
Holocene
Bellmore Formation
Wantagh Fm. silty-clay facies
Wantagh Fm. sand facies
Pleistocene Wisconsinan
Merrick Formation
Greensand
Cret.

FIGURE 3

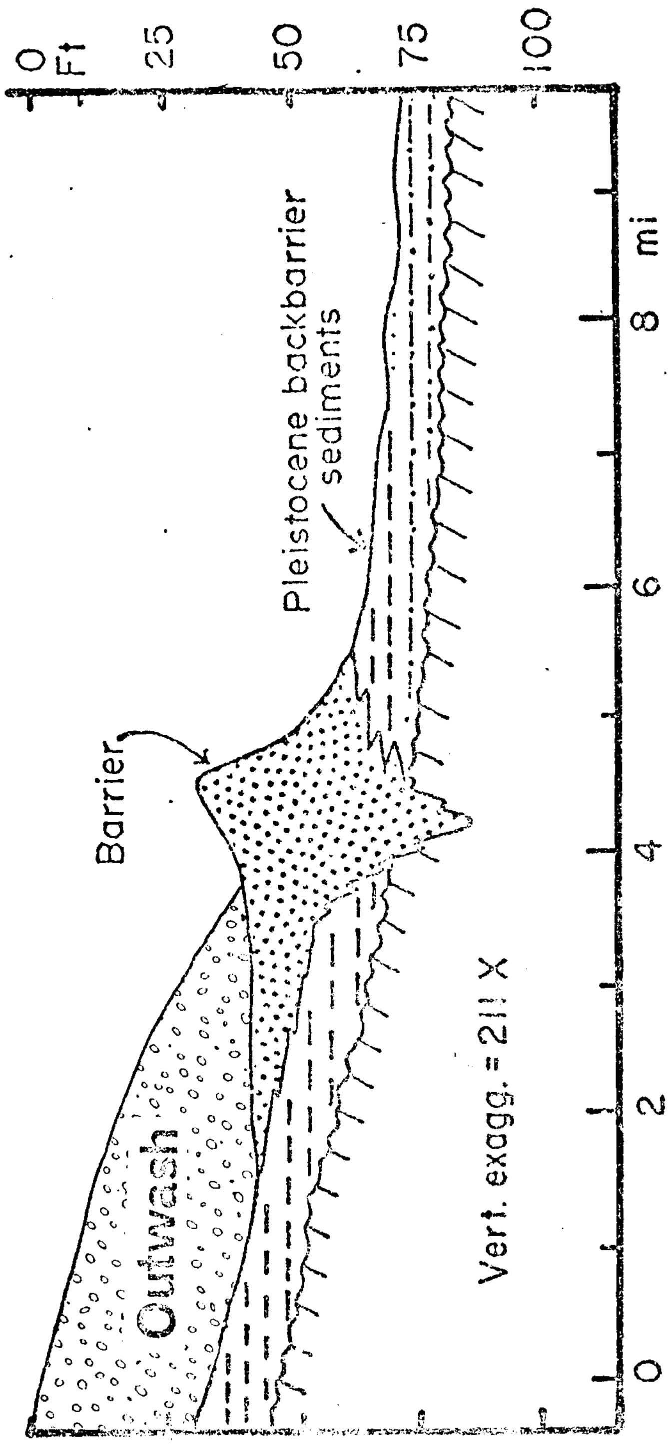

0
Ft
25
50
75
100
mi
8
6
4
2
0
Pleistocene backbarrier
sediments
Barrier
Outwash
Vert. exagg. = 211 X

FIGURE 4

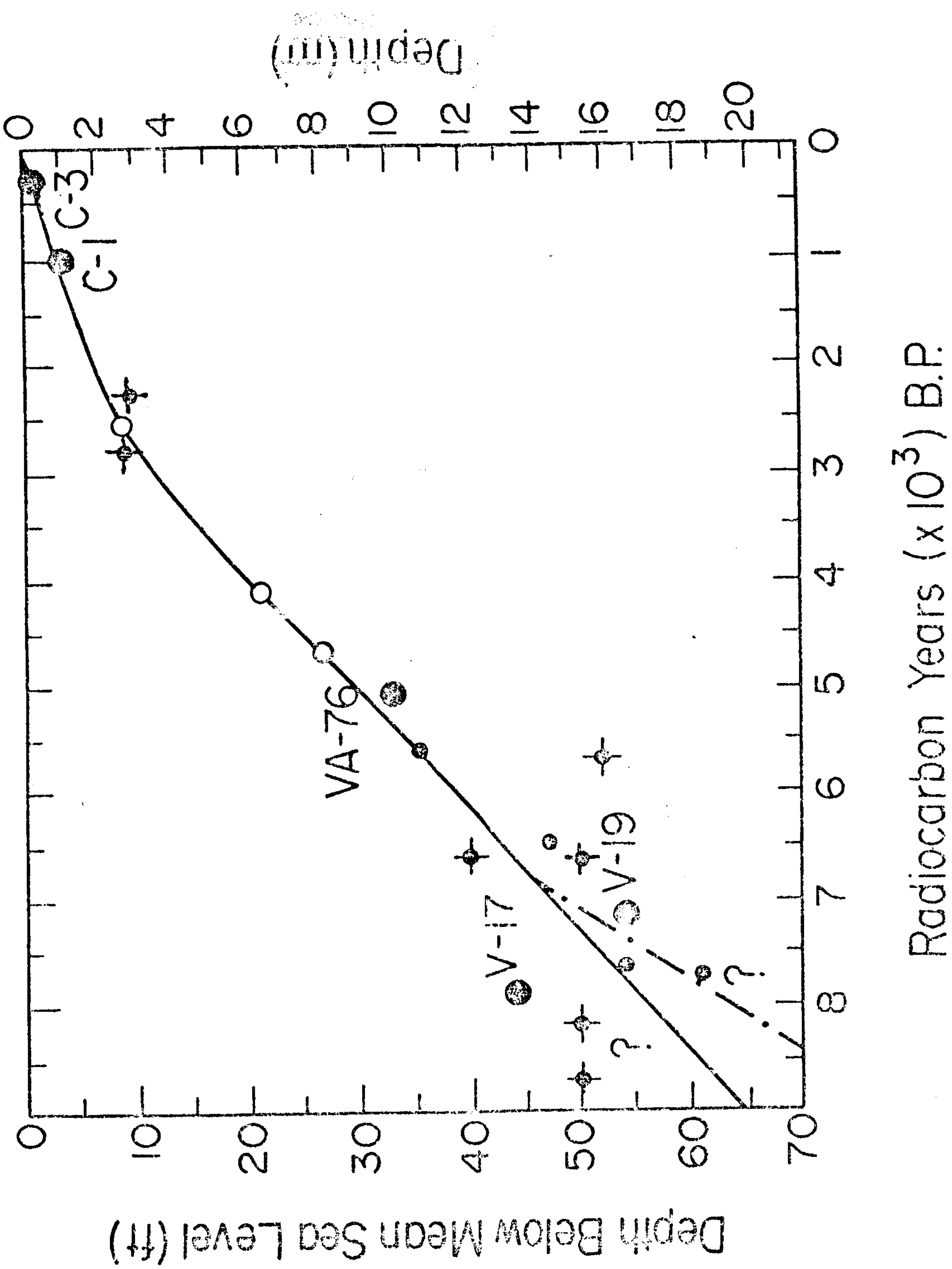

Depth (m)
Depth Below Mean Sea Level (ft)
Radiocarbon Years (x 10^3) B.P.
C-1
C-3
VA-76
V-17
V-19

FIGURE 5

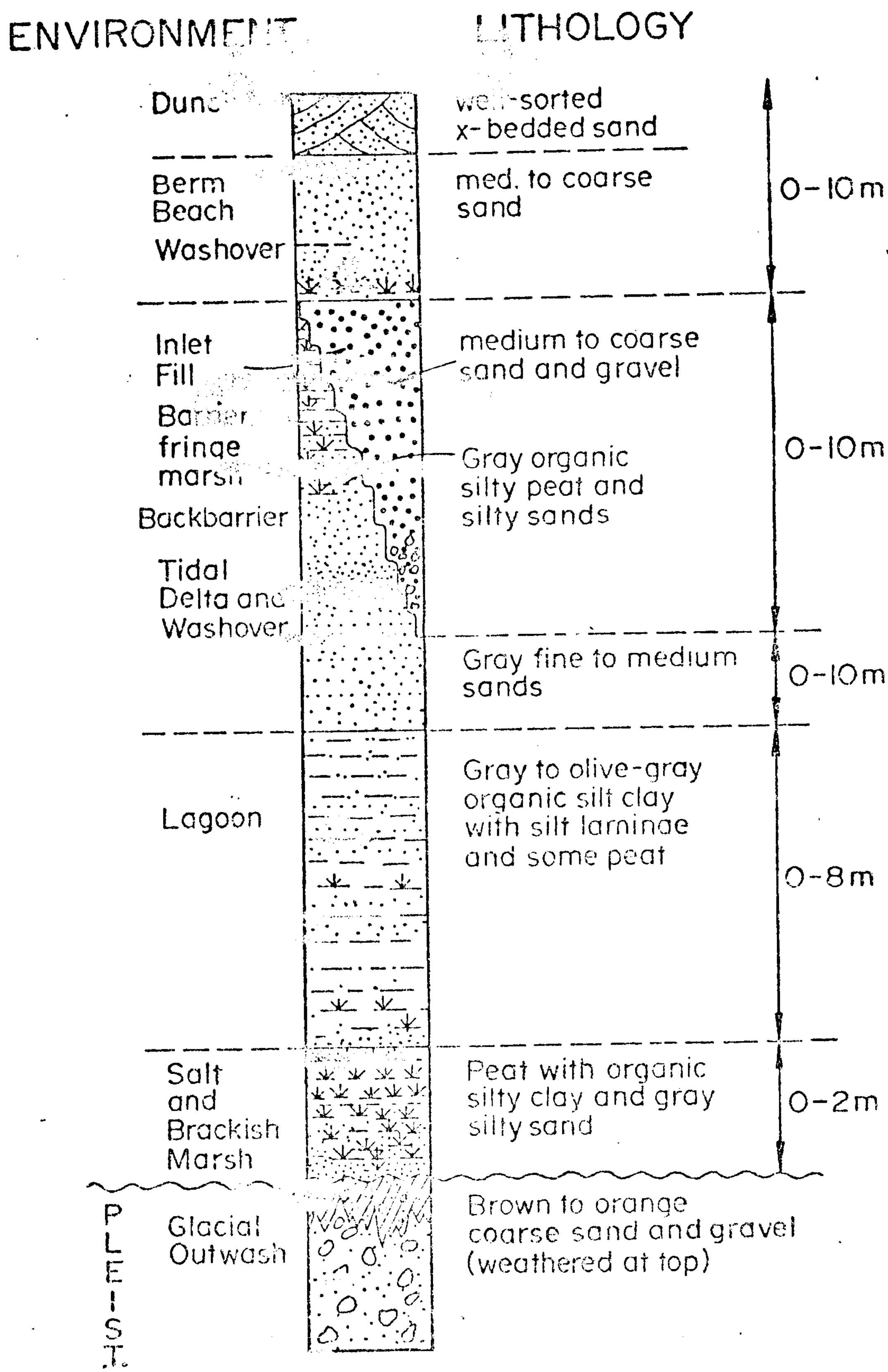

ENVIRONMENT
LITHOLOGY
Dune
well-sorted x-bedded sand
Berm
Beach
Washover
med. to coarse sand
0-10m
Inlet Fill
medium to coarse sand and gravel
Barrier fringe marsh
Gray organic silty peat and silty sands
Backbarrier
Tidal Delta and Washover
0-10m
Gray fine to medium sands
0-10m
Lagoon
Gray to olive-gray organic silt clay with silt laminae and some peat
0-8m
Salt and Brackish Marsh
Peat with organic silty clay and gray silty sand
0-2m
PLEIST.
Glacial Outwash
Brown to orange coarse sand and gravel (weathered at top)

FIGURE 6

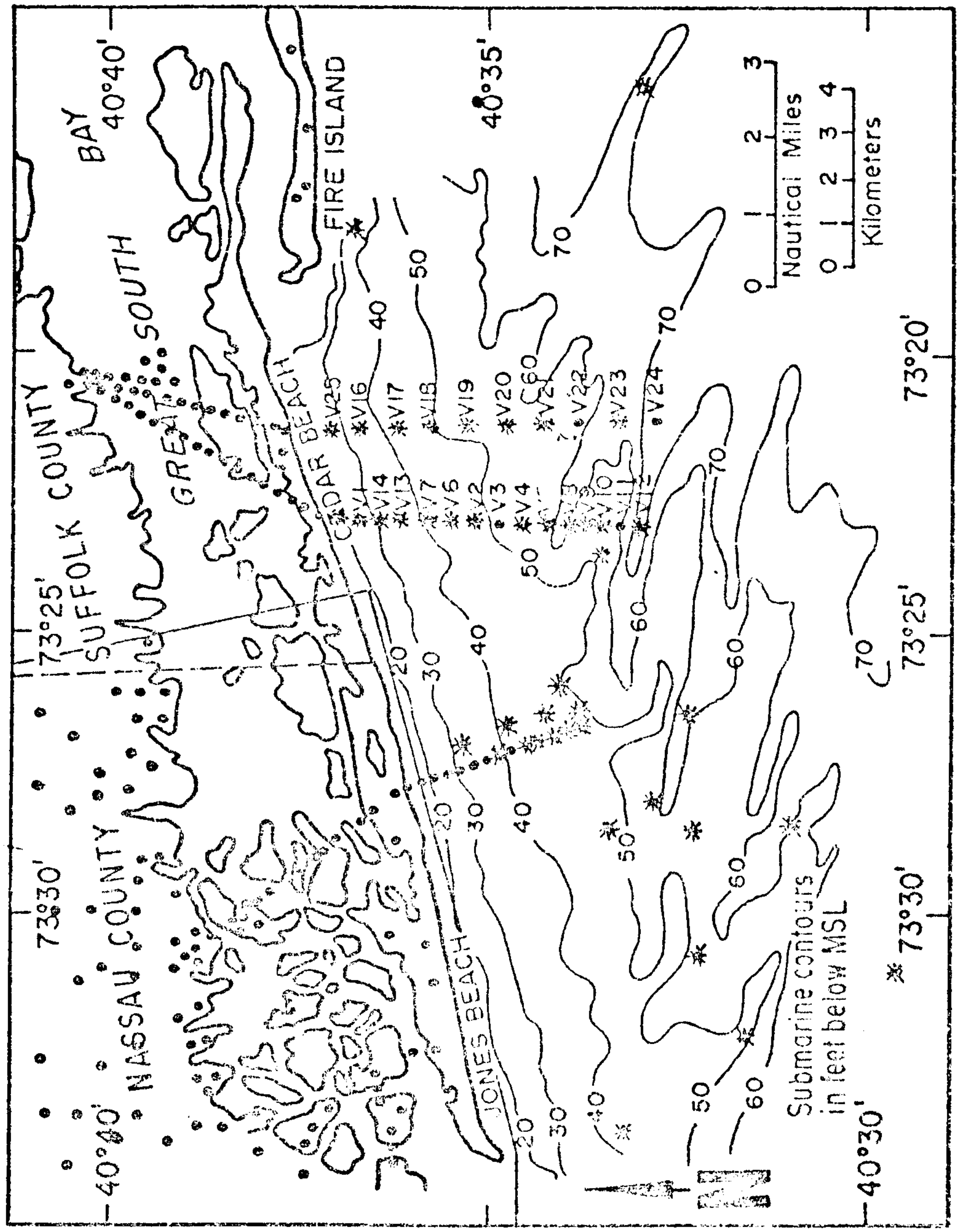

NASSAU COUNTY
SUFFOLK COUNTY
GREAT SOUTH BAY
FIRE ISLAND
CEDAR BEACH
JONES BEACH
Submarine contours in feet below MSL
Nautical Miles
Kilometers
73°30'
73°25'
73°20'
40°40'
40°35'
40°30'

FIGURE 7

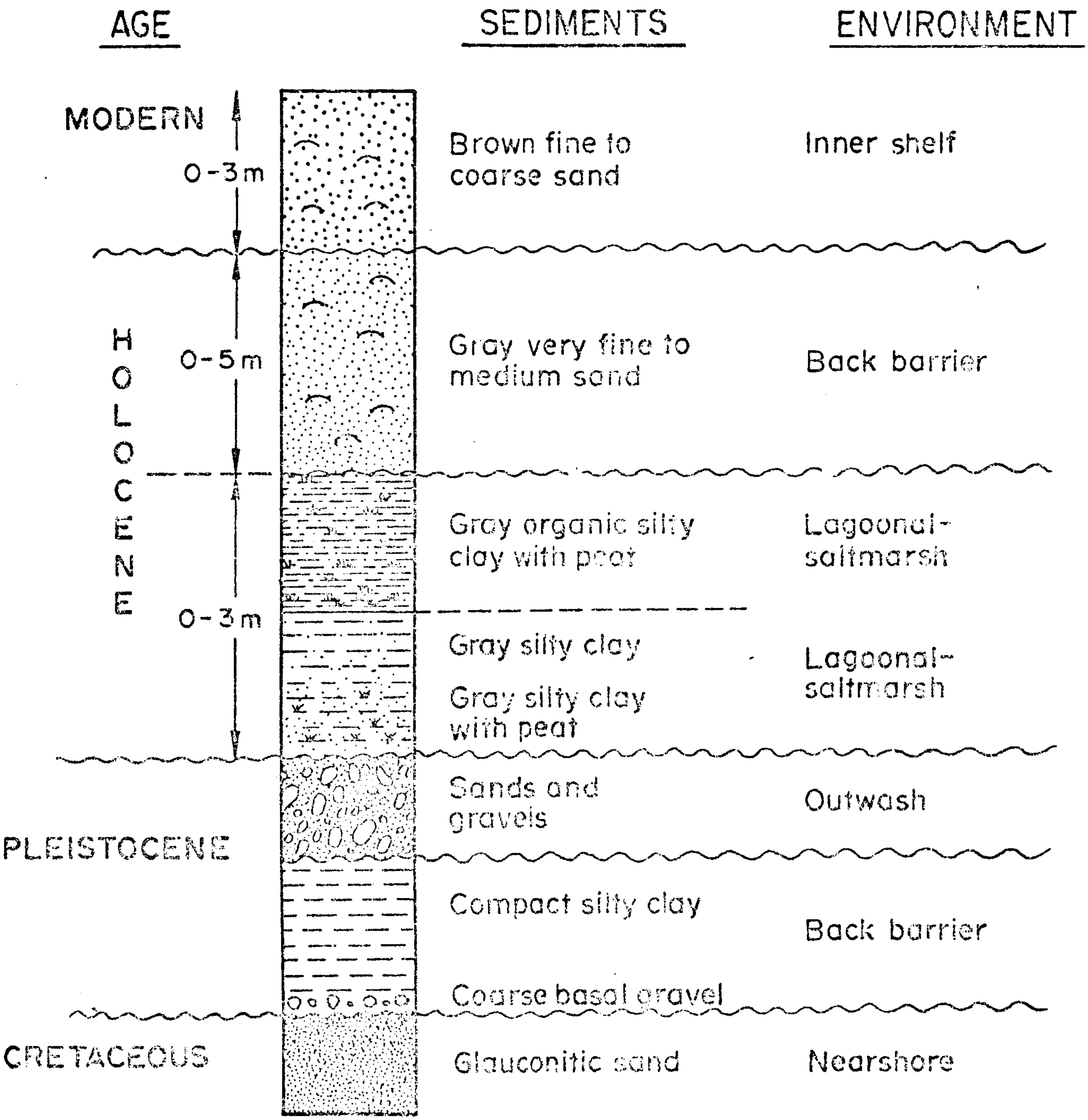

AGE
SEDIMENTS
ENVIRONMENT
MODERN
0-3m
Brown fine to coarse sand
Inner shelf
HOLOCENE
0-5m
Gray very fine to medium sand
Back barrier
Gray organic silty clay with peat
Lagoonal-saltmarsh
0-3m
Gray silty clay
Gray silty clay with peat
Lagoonal-saltmarsh
Sands and gravels
Outwash
PLEISTOCENE
Compact silty clay
Back barrier
Coarse basal gravel
CRETACEOUS
Glauconitic sand
Nearshore

Figure 8

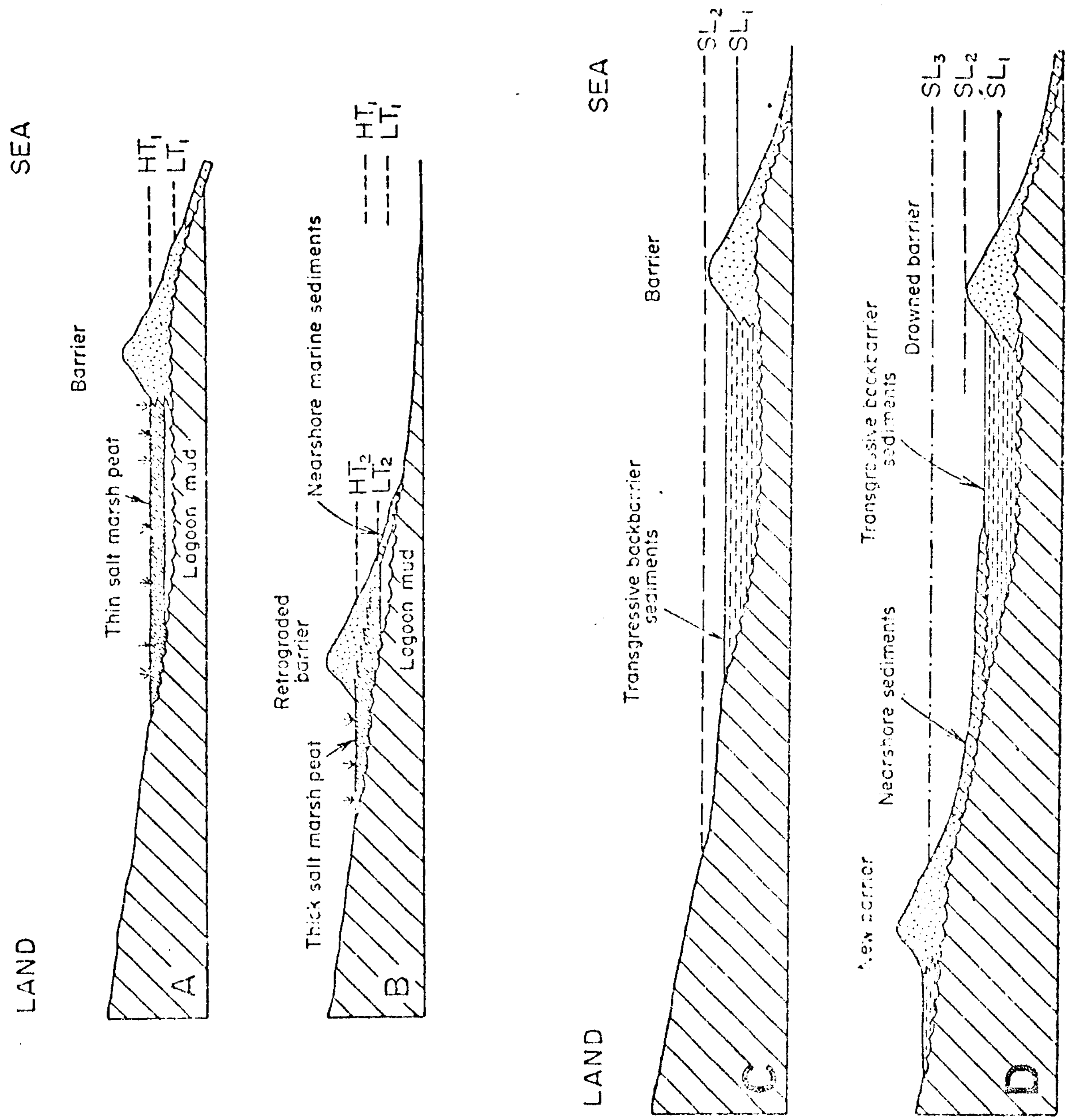
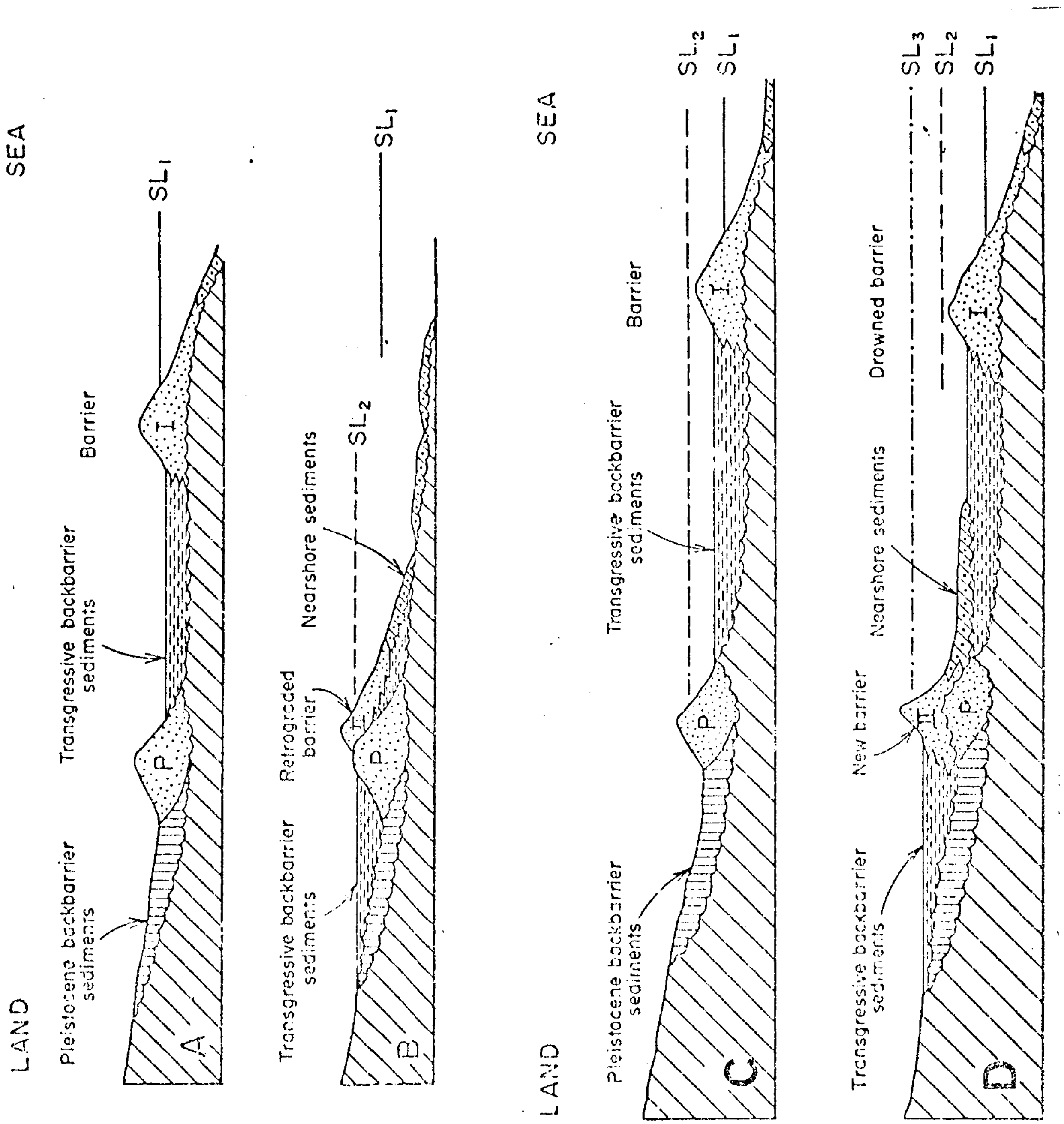

LAND
SEA
A
Barrier
Thin salt marsh peat
Lagoon mud
HT_1
LT_1
B
Retrograded barrier
Thick salt marsh peat
Lagoon mud
Nearshore marine sediments
HT_2
LT_2
HT_1
LT_1
LAND
SEA
C
Barrier
Transgressive backbarrier sediments
SL_2
SL_1
D
New barrier
Nearshore sediments
Transgressive backbarrier sediments
Drowned barrier
SL_3
SL_2
SL_1

FIGURE 9



LAND
SEA
SL1
SL2
SL3
Barrier
Transgressive backbarrier sediments
Pleistocene backbarrier sediments
Retrograded barrier
Nearshore sediments
Drowned barrier
New barrier
A
B
C
D
P
I

FIGURE 10

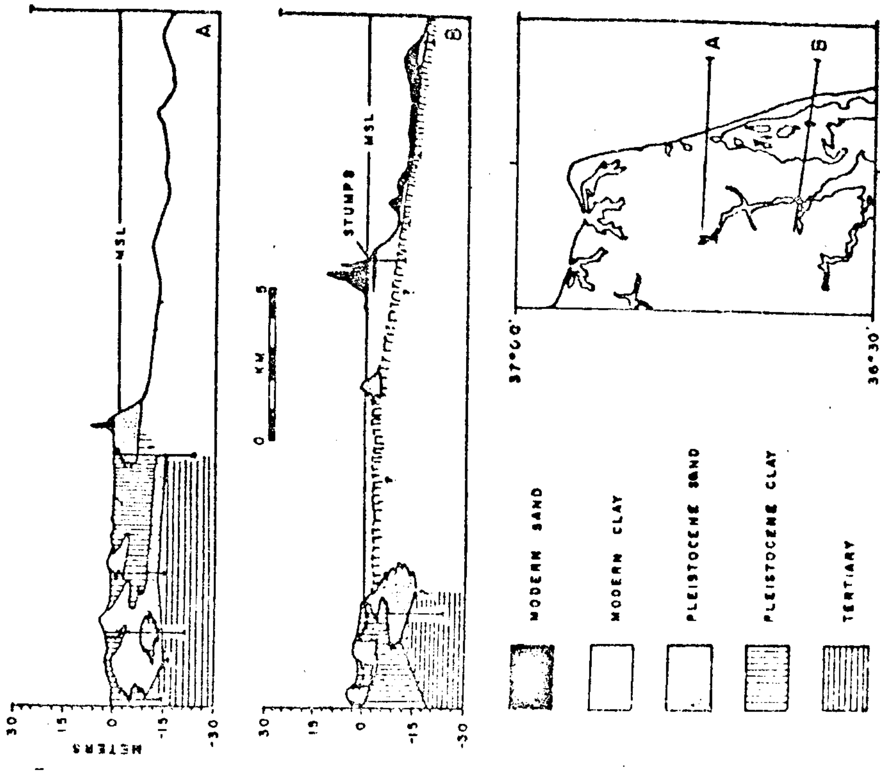


FIGURE 11B

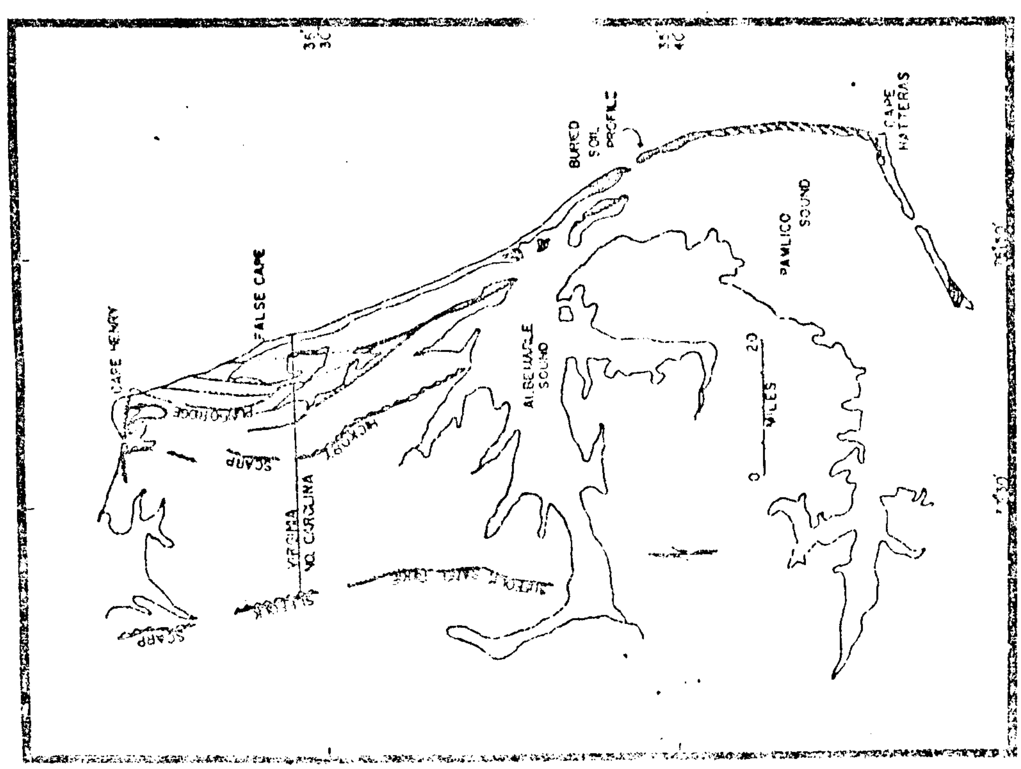


FIGURE 11A

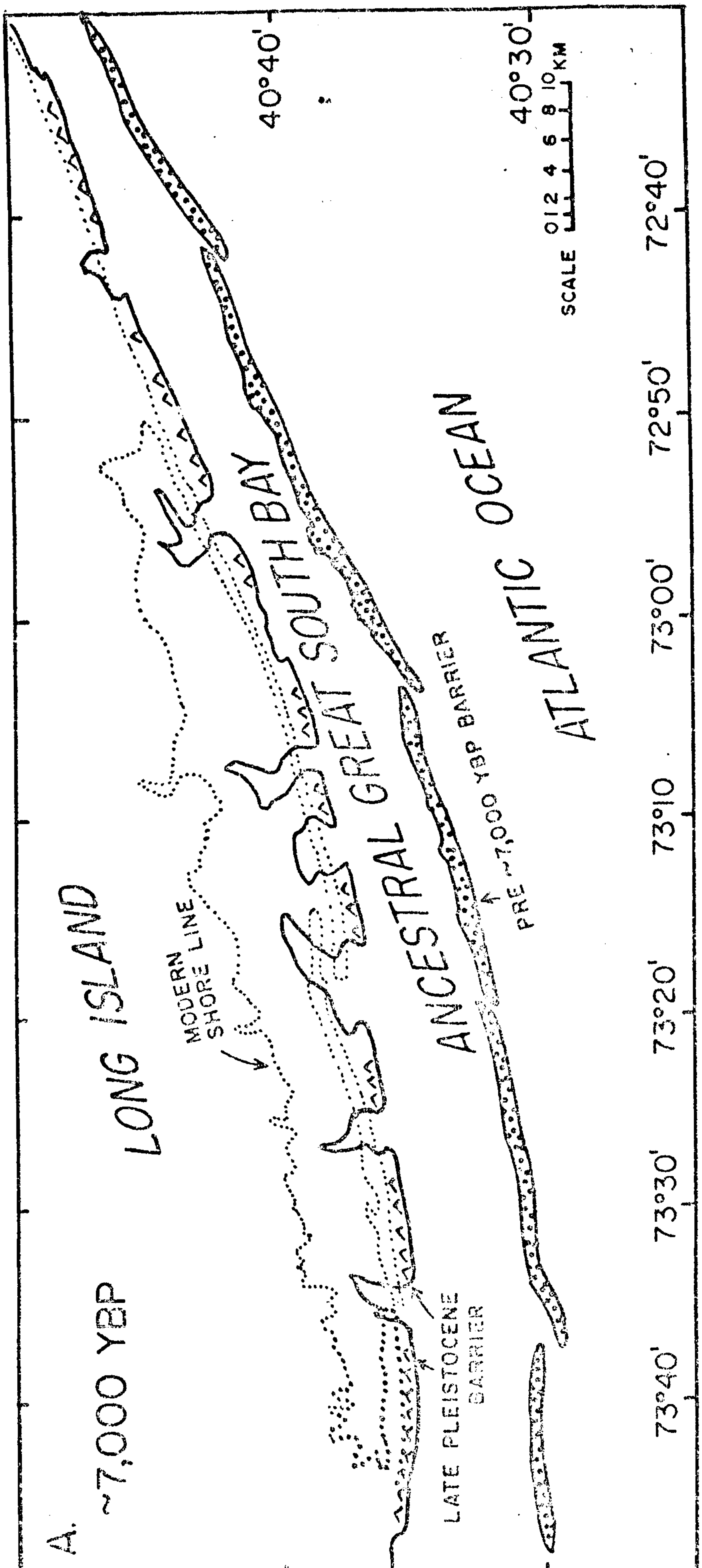
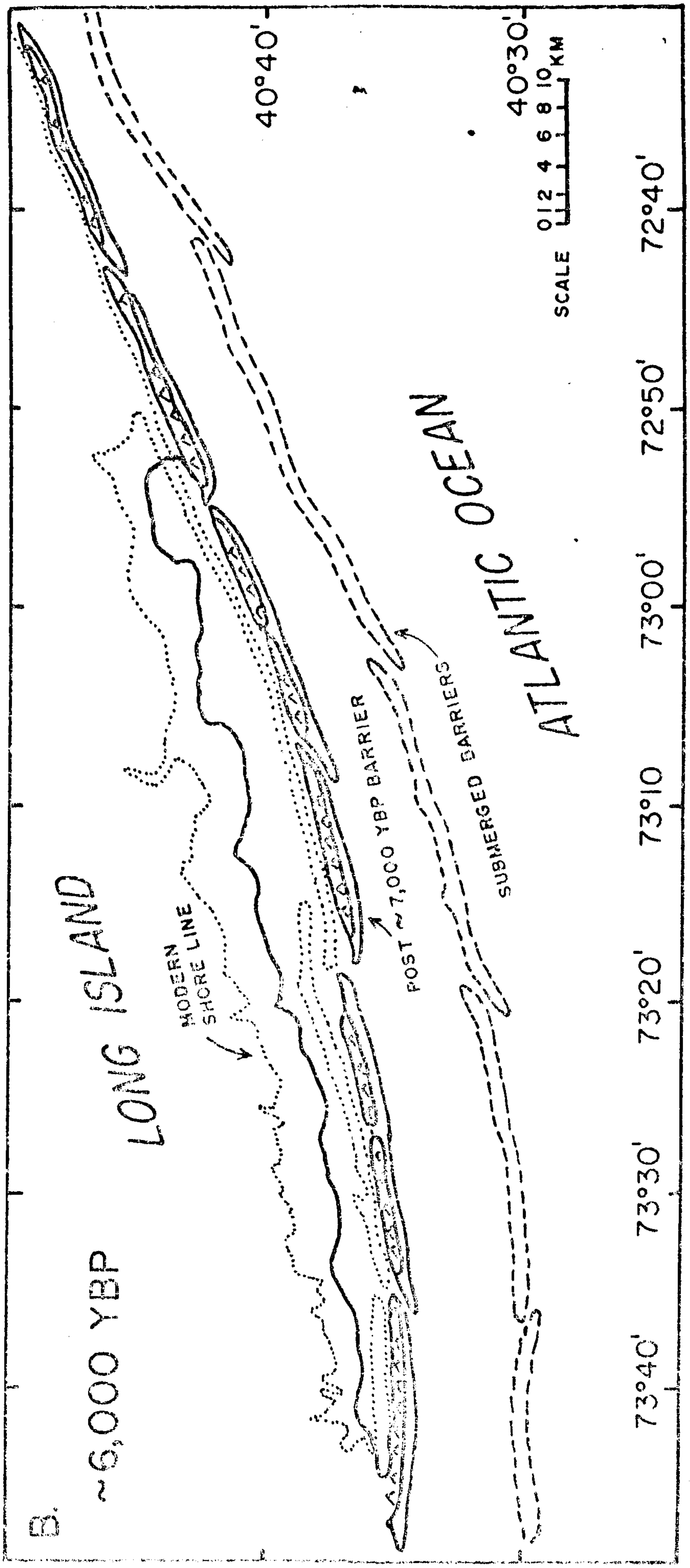

A.
~7,000 YBP
LONG ISLAND
MODERN SHORE LINE
LATE PLEISTOCENE BARRIER
ANCESTRAL GREAT SOUTH BAY
PRE ~7,000 YBP BARRIER
ATLANTIC OCEAN
SCALE 0 1 2 4 6 8 10 KM
40°40'
40°30'
72°40'
72°50'
73°00'
73°10'
73°20'
73°30'
73°40'

Figure 12 A



B.
~6,000 YBP
LONG ISLAND
MODERN SHORE LINE
POST ~7,000 YBP BARRIER
SUBMERGED BARRIERS
ATLANTIC OCEAN
SCALE
0 1 2 4 6 8 10 KM
40°40'
40°30'
72°40'
72°50'
73°00'
73°10'
73°20'
73°30'
73°40'

Figure 12 B

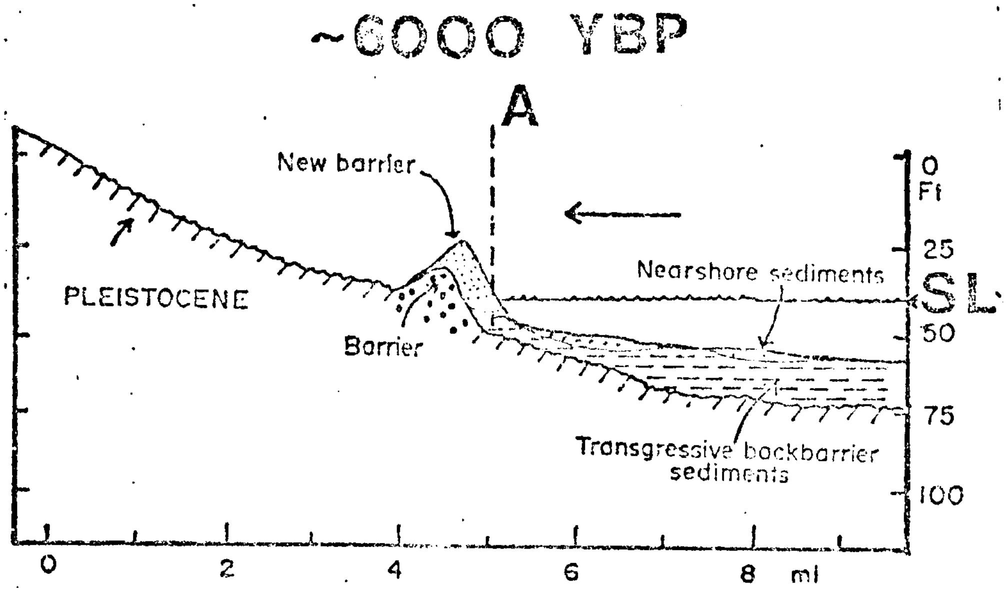


FIGURE 13A

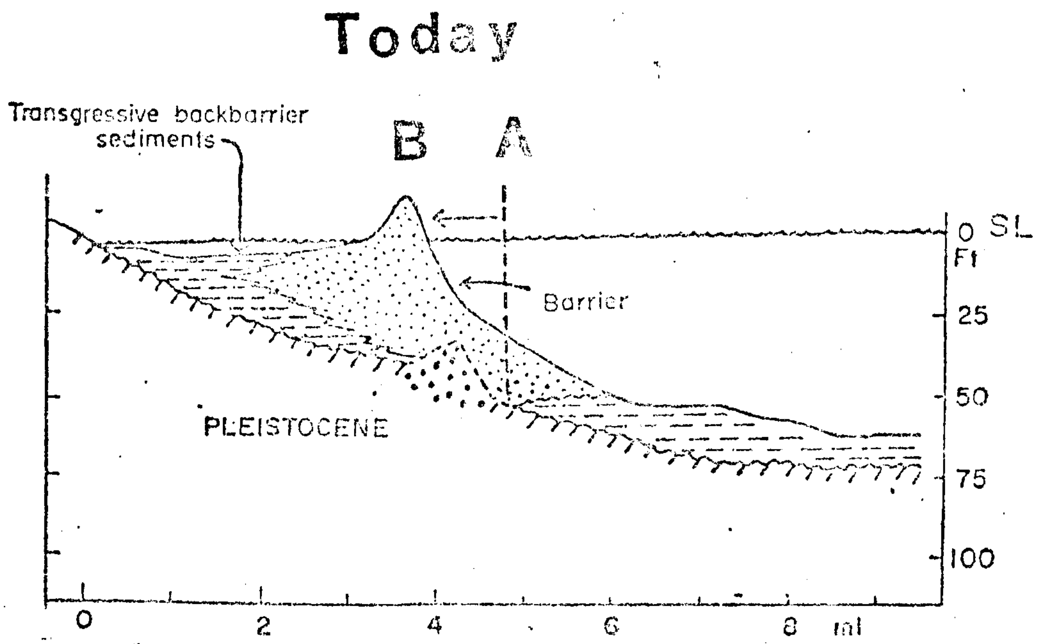


FIGURE 13 B